2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

A Neuromorphic Finger-Wearable Device for Micro-Displacement Virtual Tactile Stimulation

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***Abstract*—Conventional wearable haptic interfaces designed for virtual environments have exhibited critical limitations in conveying realistic tactile sensations. Most existing systems relied on bulky vibration actuators and simplified vibration patterns that insufficiently captured the subtle nuances and complex dynamics of natural touch. Moreover, the rigid and oversized structure of conventional actuators constrained comfortable and prolonged use, ultimately hindering user acceptance and real-world applicability. Furthermore, most systems lacked the capacity to adapt in real time to user interaction dynamics, such as exploration speed and tactile intent, resulting in disjointed and unrealistic user experiences.**

To overcome these limitations, a neuromorphic finger-wearable haptic ring was developed, incorporating micro-displacement stimulation to deliver enhanced tactile realism and signal resolution. This approach improved tactile fidelity, mechanical compactness, and user ergonomics, contributing to a reduced gap between virtual and physical sensory experiences. Critically, real-time adaptability was implemented, enabling dynamic adjustment of feedback in accordance with the user's exploration speed and touch behavior, thereby enhancing consistency and naturalness in virtual tactile interactions.

The fabricated device consists of a lightweight and ergonomic aluminum structure with an adjustable diameter (25–27 mm) for optimal wearability. It integrates a TDK PowerHap piezoelectric actuator ($12 \times 4 \times 1.74$ mm) capable of generating precise micro-displacements up to 27 μm. The actuator was strategically placed on the dorsal side of the finger, allowing mechanical energy to transmit efficiently through the finger bone and engage subcutaneous mechanoreceptors in a biologically realistic manner.

To support wireless operation, a 2.5 GHz communication module was implemented. The system transmitted only spike-event data of slowly adapting (SA) and rapidly adapting (RA) mechanoreceptors, instead of transmitting raw haptic signals. Final haptic signal synthesis was performed at a separate downstream module. This architecture significantly reduced data transmission bandwidth and latency, while maintaining high-fidelity tactile rendering. The method also optimized power efficiency and communication responsiveness, facilitating seamless mobile use.

The neuromorphic processing pipeline was grounded in biological data derived from ex vivo skin-nerve recordings using mouse hind paw preparations. Mechanical indentation and low-frequency vibratory stimuli were applied to evoke neural responses from tactile A-fibers. By analyzing the firing characteristics of SA and RA units—such as spike timing, frequency, and adaptation—key features of natural tactile coding were identified. These data informed the design of computational encoding models capable of generating spiking patterns that emulate real mechanoreceptor responses.

By utilizing these encoding models, the system successfully reproduced nuanced, naturalistic haptic experiences. The synthesized tactile feedback patterns were clearly distinguishable and accurately represented variations in material properties and interactive conditions in real time. Such encoding supported enhanced perceptual immersion and content-specific interaction in virtual environments.

To evaluate practical applicability, two hands-on demonstration scenarios were designed. The first scenario involved an automotive touchscreen interface, demonstrating the system's capability to allow users to distinguish between virtual buttons via tactile cues such as edge geometry (rounded vs. sharp), size, and perceived actuation force—all without reliance on visual information. This functionality is expected to improve user safety by reducing visual distraction during driving. The second scenario showcased a virtual texture simulation in which users experienced highly realistic representations of five material types (metal, glass, wood, fabric, silk). The tactile output dynamically adapted to the user's scanning velocity and material parameters, offering a high-fidelity, immersive tactile simulation.

These demonstrations illustrated the potential of neuromorphic haptic technology in advancing tactile interaction fidelity in virtual environments. By delivering biologically grounded, differentiated tactile signals, the system offers a compelling platform for applications ranging from in-vehicle user interfaces to immersive virtual and augmented reality experiences. Future research will focus on system miniaturization and the advancement of fully wireless operation to support broader adoption and ease of integration in real-world contexts.

***Index Terms*—Neuromorphic haptics, Wearable device, Virtual tactile perception, Rodent-derived neural patterns, Piezoelectric actuator, Electrophysiological modeling, Virtual interaction**

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF, No. RS-2023-00302489) and the Electronics and Telecommunications Research Institute (ETRI) grant (25ZB1330, Brain-morphic decoder-encoder technology development) funded by the Korea government (MSIT).